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A review of technology diffusion models with special reference to renewable energy technologies

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ABSTRACT

Diffusion of renewable energy technologies (RETs) are driven by policies and incentives due to their inherent characteristics such as high upfront costs, lack of level playing field but distinct advantages from energy security, environmental and social considerations. Even after three decades of their promotion, only 20–25% of their potential has been realized. The theory of diffusion modeling allows analysis of diffusion processes and study of growth rates of different technologies and underlying diffusion factors. Their applications have focused on commercial and consumer products such as television, automobiles and IT products and their applications to RETs have been limited. Diffusion analysis of RETs have been based on barriers' to RET adoption and techno–economic, learning and experience curve approaches. It is observed that these diffusion models when applied to commercial products do not deal with the issues of policy influences which are critical to RET diffusion. Since policies drive RET diffusion, the models for analyzing RET diffusion should allow establishing explicit relationships between the diffusion parameters and policies and their impact on diffusion rates. Given the potential of renewable energy technologies for sustainable development, the aim of this paper is to review different diffusion theory based models and their applicability to RET diffusion analysis.

Contents

1. Introduction

The diffusion of an innovation is a process by which an innovation is communicated through certain channels over time among the members of a social system. It is noted that the diffusion processes in general follow an S curve (Fig. 1). There are diverse examples for depicting this S shaped pattern in the natural growth of many phenomena including the initial diffusion of Cistercian monasteries in Europe one thousand years ago and life expectancy of creative geniuses (such as Mozart) [1]. Further, different diffusion models have been used, particularly since the 1960s to capture this diffusion trend in the form of mathematical equations [2]. These models have been applied to study various diffusion processes that include population of cars, television, computers, consumer goods, etc. as well as frequency of economic booms and busts, number of fatal car accidents, incidence of major nuclear

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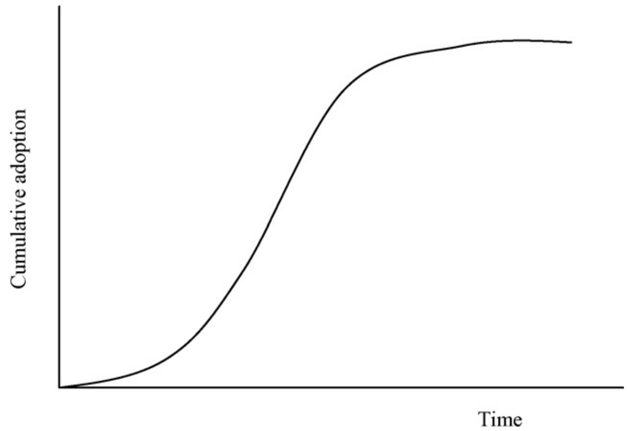

Fig. 1. Diffusion curve – cumulative adoption vs. time.

accidents, technological change in the computer industry and number of deaths from AIDS [3–5]. Diffusion is also seen as a five-stage process – awareness, interest, evaluation, trial, and adoption [6]. They correspond to different stages of consumers' adoption during market development classified as innovators/early adopters, early and late majority and laggards according to the time of adoption, since the technology is introduced in the market (Fig. 2). However, there is an uncertainty with regard to the extent and time for diffusion of technology. For example, nuclear fission reaction (invention) was used for the first time in a reactor to produce commercial power (innovation) that generated 20% of the US electricity after 40 years.

Diffusion of environmentally sound technologies is essential to realise sustainable development goals. The diffusion rates are context specific – dependent on socio–economic, technological, and institutional factors. These factors that facilitate or hinder diffusion and drive the process are inter-linked making diffusion a complex phenomenon [7]. Renewable energy technologies (RETs), for instance are mainly driven by impending environmental and energy security considerations arising from use of fossil fuel based energy (from coal, oil and gas) and the fact that fossil based energy sources are not infinite. Unlike other commercial products or technologies, RETs further receive significant financial and fiscal incentives from the government or public agencies for their promotion or adoption. However, despite direct policy efforts and inherent environmental and socio–economic advantages of RETs, their rate of spread has been low. It thus reinforces the challenges of taking a new technology to the market place. The aim of this paper is therefore to review different diffusion models and applications and assess their suitability as a conceptual tool to study RET diffusion.

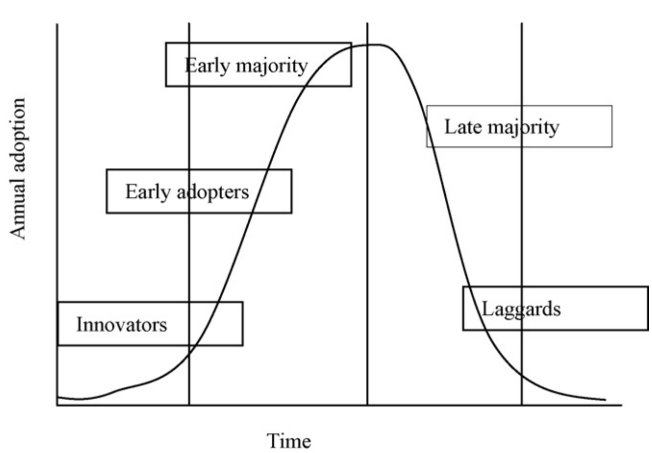

Fig. 2. Diffusion curve – adopters vs. time.

2. A brief review of technology or product diffusion models and applications

Modelling technology diffusion processes was initially derived from the theory of growth of a colony of biological cell in a medium. Since the growth of a cell would be limited due to limited nutrients or space, it would slow down and saturate resulting in an S curve pattern. Similarly, technology diffusion models assume that the growth of a technology or an innovation is dependent on the total potential adopters and the rate of increase is represented by the following fundamental diffusion equation referred to as the internal influence diffusion model.

$$\frac{dN}{dt} = bN(t)(N^{u} - N(t)) \tag{1}$$

where $N(t)$ is the cumulative adoption at time t and N^{u} is the ultimate potential; b is the coefficient of diffusion.

Eq. (1) is basically a logistic growth curve and is directly used in technology diffusion which assumes that diffusion process is influenced by the previous adopters. If the influence on diffusion is external, the equation for the external influence model is given by Eq. (2) below as:

$$\frac{dN}{dt} = [a(N^{u} - N(t))] \tag{2}$$

where $N(t)$ is the cumulative adoption at time t and N^{u} is the ultimate potential; a is the coefficient of diffusion.

A mixed influence model which combines the above Eqs. (1) and (2) was first presented by Bass to represent the first purchase growth of a new product durable in marketing [8]. The Bass model is a mixed influence model with three parameters p, q and m; p represents the coefficient of innovation (a in the above equation) and q is the coefficient of imitation (b in the above equation = q/m) and m is the total potential. The Bass diffusion model is given by:

$$\frac{dN}{dt} = \left[p + \frac{q}{m}(N(t))\right][m - N(t))] \tag{3}$$

Mahajan and Peterson [9] classify diffusion models as follows:

(1) Fundamental diffusion models (internal, external and mixed influence): these models basically assume that the diffusion process is binary, there is a distinct and constant total potential, coefficients are constant over time, etc.
(2) Flexible diffusion models: the assumptions remain similar to fundamental diffusion models but is relatively flexible with respect to point of inflection (where the diffusion rate is maximum) or symmetry with respect to point of inflection.
(3) Refinements and extensions: many of the assumptions were modified to develop improved or revised diffusion models that are sub-categorized as under:
   a. Dynamic diffusion models: this considers the maximum technical potential as dynamic and not static,
   b. Multi innovation diffusion models: the innovation is considered as not completely independent of all other innovations but independent in a functional sense and are complementary, contingent and substitutes for other innovations,
   c. Space and time diffusion models which assumed primarily that the growth in the number of adoptions in each region would vary and the relative number of adoptions would be

greater in those regions closest to the regions of innovation origination,

d. Multistage diffusion models which consider adoption as multi stage process and not binary,
e. Multi adoption models capture repeat purchases and
f. Finally, diffusion models with influencing/change agents, which consider diffusion as not just a function of time but coefficients as a function of technology specific parameters.

Table A1 provides examples of the above diffusion models categories and applications [9]. Meade and Islam [2] classified diffusion models as: (a) models for cumulative adoption and (b) non-linear autoregressive models (please refer Table A2). An attempt on rationalization of different diffusion models [10] indicate that most diffusion equations are reduced to two parts. The first part represented in the form $G(1-F)$ as a function of potential adopters and absorbing the remaining terms in $A(f)$ which is a conversion factor and determines how many of the potential adopters can be converted; F represents the fraction of adopters at any given time and $0 \leq A(F) \leq 1$ and $0 \leq G(1\text{-}F) \leq 1$ (please refer Table A3).

There are several notable reviews of diffusion modeling approaches [11–14,5,15,2]. They show the rich and increasing knowledge on theoretical and empirical research in the diffusion of new products, services and technologies. In such reviews the advancement and improvements of the models are covered. It is highlighted that Robinson and Lakhani [16] introduced marketing variables in the parameterization of the models and examined optimal pricing policies associated with the diffusion of new products. As the diffusion processes are influenced by many decision variables, a generalized Bass model (GBM) was developed. The GBM was considered useful for managerial purposes when possibly the empirical support for cases where prices and advertising data are decision variables were used though the simple Bass model fits the data without including the decision variables, an explanation that is lacking in the other diffusion models that include decision variables. Norton and Bass [17] attempted diffusion of successive generations of technology and Gatignon et al. [18] generalized the models to consider innovations at different stages of diffusions in different countries. In all the diffusion models, the estimation of parameters and its interpretation is central for assessment or quantification of the influence of the diffusion process. Several estimation procedures are also deliberated in the literature and in the diffusion model context, they are generally a non-linear problem. Therefore, most attempts of parameter estimation are linear transformations followed by ordinary least square (OLS) methods. Some of the techniques suggested for parameter estimations include in addition to OLS, algebraic estimation (AE), non-linear least square and maximum likelihood estimation. Meade and Islam [15,2] argue that the empirical comparisons have received least attention. The choice of diffusion models and parameter estimation methods are specific to their applications for specific situations and requirements. It is important that the selection of the model is guided by appropriate forms of parameters than relying on any mathematical expression which fits the data.

2.1. Applications of diffusion models

There are numerous examples in literature on the use diffusion modeling for various applications. Mahajan and Petersen highlights the three typical uses – normative, description and forecasting applications of diffusion models. Mahajan et al. [5] highlight the use of new product diffusion models and are also illustrated many prelaunch, launch and post launch new product strategic decisions. For instance, deciding on the timing of introduction of a new product in the market and uncertainty as to its performance with regard to pricing/advertising. Among the diffusion models, the Bass model has been extensively used for various type of diffusion analysis. Bass [19] cites that there have been hundreds of applications of the Bass model itself. A brief review of applications of diffusion models show (in addition to what is included in Appendix A) that the applications are broadly in three types: (1) study of general spread of new technology or innovation (2) examine pricing as a diffusion variable and (3) forecasting purposes – demand, etc. Table 1 below highlights a few examples of specific application of selected diffusion models. As can be seen, diffusion models have been applied extensively in commercial consumer goods. Also, there have been limited applications in developing countries.

3. Diffusion analysis of RE technology and applications

In the above analysis, it was evident that there is limited use of diffusion models in renewable energy technology (RET) analysis. RETs convert natural resources such as solar, biomass, wind, and hydro into useful forms of energy (electricity/thermal or other requirements). Their adoption have been mainly driven by impending environmental and energy security considerations arising from use of fossil fuel based energy (from coal, oil and gas) and the fact that fossil based energy sources are finite. Unlike other commercial products or technologies, RETs have been promoted with start-up support for demonstration projects, followed by significant financial and fiscal incentives from the government or

Table 1
Examples of application of selected diffusion models.

Type of diffusion analysis	Author, Year	Models	Application/Focus (model being used for)
Spread of Technology or products	Desiraju et al. (2004) [20]	Logistic Model	Diffusion of new pharmaceutical drugs in developing and developed nations. Grocery brands
	Bass (1969) [8]	Mixed influence model	Consumer products
	Bass (2004) [19]		Satellite TV, radio, LCD projector, medical technology, wireless phones and wireless internet phones(3G)
	Bewley and Griffiths (2003) [21]	Flexible logistic (FLOG)	Penetration of CDs in the sound recording market.
	Bewley and Feibig (1988) [22]	Flexible logistic (FLOG)	Telecommunication
Price as a decision variable in diffusion	Bottomley and Fildes (1998) [23]	Internal, external and mixed influence models	Consumer durables
	Jain et al. (1991) [10]		
Demand/growth diffusion models and forecasting	Chow (1967) [24]	Gompterz's Curve	Demand for computers
	Anderson et al. (2008) [25]	Technology forecasting data envelopment analysis	Wireless communication

The above examples are from the theoretical diffusion models at aggregate level.

public agencies. Despite direct policy efforts and inherent environmental and socio–economic advantages of renewable energy technologies, diffusion of these alternative forms of energy has been very limited.[1] It reinforces the challenges of taking a new technology to the market place as well successful diffusion of some RET's in specific locations (e.g. wind energy technologies in Spain or Germany; small hydro technologies in China and India).

RETs are characterized by low load factor (wind, small hydro), need for energy storage (solar PV), small size (in kW range), high upfront costs and absence of level playing field (subsidies for conventional fuels). These factors have put RETs at a disadvantage, and thus the need for special support for the increased diffusion of RETs. RET diffusion analysts have mainly focused on analytical frameworks based on policies or barriers to diffusion of RETs. The process of commercialization of RET occurs in stages. Lund [26] describes the process as beginning with Research and Development, followed by demonstration and pilot production. This leads to early market introduction and finally, market diffusion. While different RETs are at different phases of market development, the research in diffusion analysis in renewable energy sector points towards the following approaches.

3.1. Economies of scale, experience and learning curve approaches to establish cost reductions

Learning and experience curves have been used to study the diffusion processes of RETs. The learning curve concept represents the technological progress associated with a technology, i.e. the improvements induced by experimentation, implementation and R&D throughout the production process, directed by social and economic policies as well as economic opportunities. It is an indicator of the marginal innovations which occurred in a technology or, alternatively, is the product of increasing productivity induced by experience.

Lund [27] estimated financial resource required for RET based on an analysis of costs and returns on per unit production cost and cost reduction due to learning by doing. Ibenholt [28] compared utilization of wind energy in three countries Denmark, Germany and the United Kingdom by applying learning curve to study empirical relationship between costs and accumulated production or capacity. By combining an analysis of learning curves with an analysis of policy programmes, important factors that determine the slope of the curves, this paper concludes that utilization of wind energy in different countries greatly differs due to aerodynamic condition and differing policies. Most of the technological studies based on learning curves for renewable energy sources typically discuss how the costs have been reduced over time and a few cased whereas the analyses are on why the costs have been reduced [29]. There are also a lot of studies concerning technology policies, and how to promote renewable energy sources [30].

Isoard and Soria [31] explored the respective contributions of the effects of learning and returns to scale in the capital costs reduction pattern experienced by renewables. It is widely acknowledged that, with low production levels, the long-term unit cost curve may exhibit increasing returns to scale, whereas with a high scale of production, decreasing returns to scale may occur. The results indicate that learning by doing and returns to scale both are significant for wind and solar PV Technologies. The wind and solar PV technologies both showed flexible returns to scale, for wind ranged from 0.80 to 1.01 and for PV it ranges from 0.70 to 0.97. Further, it is concluded that an optimal production is required to achieve cost reduction. The uncertainties related to technical aspect and future trend of market price and price distortion form major diffusion barriers. It is further justified that RET diffusion needs favorable policies and initial support to take full advantage of scale of production. Additionally, these measures may be suggested to compensate for the structural inertia exhibited by the power sector and to launch the 'lock-out' of the technologies currently in place.

Neij [29] used experience curves to analyse the prospects for diffusion and adoption of RETs, with special emphasis on wind turbines and photovoltaic (PV) modules. The analysis shows that the possibility of cost reductions of RETs is greater as compared to conventional energy technologies. However, large investments are necessary to make wind turbines and PV modules economically competitive with conventional power plants. The results indicate that the prospects for diffusion and adoption of wind turbines and PV modules will increase if policy instruments are used to bring about diffusion. The experience curve is given by:

$$C_{\mathrm{CUM}} = C_0.\mathrm{CUM}^{\mathrm{b}}$$

where C_{CUM} is the cost per unit as a function of output, C_0 is the cost of the first unit produced, CUM is the cumulative production over time and b is the experience index. The experience index is used to calculate the relative cost reduction (1-2b) for each doubling of the cumulative production. The value (2b), called the progress ratio (PR), is used to express the progress of cost reductions for different technologies. A PR of 80%, for example, means that costs are reduced by 20% each time the cumulative production is doubled. It was emphasized that coal-burning and nuclear electricity generating units have shown a cost increase over the years. While the experience curves for small-scale plants and module technologies have shown a more progressive behavior, thus indicating the possibility of cost reductions for renewable energy technologies, such as wind turbines and solar photovoltaic (PV) modules, the prospect of diffusion and adoption of renewable energy technologies however was found to depend on difference of rate of cost reduction comparative to other conventional technologies.

Jacobson and Johnson [30] emphasized a need for government intervention to promote RETs up to the extent where costs reduce due to learning and mass production of these technologies. They identified the emergence of 'prime movers' that can lead the transformation process. In particular, the key role that a local capital goods industry can play was highlighted. The 'prime movers' can both be larger firms and networks of smaller firms. In a scenario with a distributed energy system made up of a whole set of different technologies, it may well be that networks take on the role of 'prime movers'.

3.2. Economic analysis of RETs for its viability among the given alternatives

Rio and Unruh [32] surveyed the diffusion of wind and solar PV power in Spain using evolutionary economic model. They argue that economic and institutional factors play crucial and key roles in fostering or inhibiting diffusion. The paper first elaborates a theoretical framework that builds from an evolutionary economic perspective and takes into account market, technological and institutional factors which influence diffusion. The framework is then applied to wind and PV, set within the context of the Spanish energy sector to explore the causal factors for the differential diffusion rates of wind and PV technologies. The study reveals that despite having vast potential for wind and solar, the contribution of solar PV power is less than wind power. The main factor is lock-in of other alternatives which are viable in terms of returns and easy financing option. Collantes [33] proposed a technological

[1] The sole exception is wind energy technology, which has had the maximum growth and penetration in India as well as globally.

substitution model to study the growth rate of market share of fuel cell vehicles. Shukla and co-workers [34] analyzed the penetration of RETs using the bottom up MARKAL Model – an energy systems model, ideally suited for techno–economic analysis. Ardente and co-workers [35] present energy performances and life cycle assessment of RE technologies.

3.3. Stakeholders' perspectives and barrier analysis frameworks and barriers mitigation approaches

Jacobson and Johnson [30] suggested that the technological system perspective is most suitable for study of RETs and applied an analytical framework based on three agents, namely, creating a knowledge base, institutional changes (as they would be nascent for new technology), and prime movers (key actors in the creation of new technological systems) that could influence the diffusion process of renewable energy technology. Reddy and Painuly [36] collected information by interviewing stakeholders (individuals, organization, and manufacturer and policy makers) on factors influencing the rate penetration of renewable energy technologies to conclude that government intervention is needed to remove the barriers and increase the contribution of RETs in energy sector. Peter et al. [37] applied Rogers' model to identify the diffusion factors of solar PV – these included financial incentives, government led initiatives, reduction of investment costs, and increase in reliability, dissemination of information and environmental awareness.

3.4. Policy analysis and influences on the RET adoption

Several articles discuss the influence of policies and institutional frameworks on the growth of RETs. It has been noted that not all policies impact favourably and due to regular changes in policies (like tariffs and other criteria) and the uncertainty of compliance period, the effectiveness of policy decreases [38]. Many of the policy elements especially the case of subsidies for wind technologies, which were phased-in and phased-out, and for which not only the extent of support but also the criteria have been under continuous revision in many countries. In Netherlands for instance, the early replacement of subsidies with fiscal instruments in the case of wind projects is slated to have had negative consequences on the financing costs incurred by private developers. Dinica [39] proposed an investor-oriented perspective to analyze the diffusion potential of support systems for RETs, particularly, policies such as feed in tariffs and quota model. Though the RETs have huge potential to fulfill the global demand of electric power, the initial cost incurred in setup of such technology and difficulty in getting financial support is a major barrier for the technology diffusion.

Ravindranath et al. [40] analyze RET policies and point out to the continuing barriers to the large-scale adoption of RETs in India. Bhatia [41] noted that the incentives and subsidy programs for biogas engines in India were arbitrarily designed and were not profitable for adopters. This was based on an analytical conceptual framework that categorized various factors which influence the diffusion and adoption process as technology characteristics, micro-environment, government's role, types of users and market structure. It was further argued that lack of large-scale success does not imply the inappropriateness of technology; rather efforts would be required to create an environment to promote the adoption of such technology. As the adoption process begins with the interaction of user, social and government in a complex manner, it is necessary to understand those interactions from areas where it has been successfully adopted and to create similar environments in areas where rate of adoption is less. Similarly, a review of dissemination of cooking energy alternatives in India – a review by Pohekar et al. [42] points to low dissemination of biogas and solar cooker and highlight the need for government intervention in terms of favorable policy and incentive to promote their use in households.

Theocharis and Stamboulis [43] and Lund [44] point out environment pressures and Kyoto mechanisms driving the RET adoption and innovations. Based on Roger's theory, Theocharis and Stamboulis [43] recognized the interaction of technological, social and organizational elements require a policy that will enhance supply, more especially, demand. The pattern of diffusion of the new paradigm, they indicate still escapes the attention of policy makers and analysts. They also indicate barriers to the sustainable diffusion of RETs and identified the main problem to lie in the implicit assumption of policy makers that diffusion is simply a matter of substitution. Purohit and Michaelowa [45] presented a diffusion analysis of solar PV pumps in India and estimated the CDM potential for SPV pumps. They argued that though the governmental subsidy is available to farmer, still other options (electric and diesel pumpsets) are more attractive. Theocharis and Stamboulis [43] argued that strategy and policy tend to focus on the performance of individual RETs. The project-based measures fail to take into consideration two dynamic elements (1) the need for technological choice and regulation to exploit the role and the experience of users; and (2) the multiple economic impact of the mass diffusion of RETs, initially in the construction and service sectors of the economy. Based on their analysis, they suggested that a successful renewable-oriented policy should be the conceptualization of renewables as a radically different technological system from that of conventional sources (fuels and nuclear). Also, the development of RETs was connected with the parallel growth of innovation systems with national or regional character.

Purohit and Kandpal [46] attempted projected levels of dissemination, energy delivery and investment requirements for RETs for irrigation water pumping in India using available diffusion models. Rao and Kishore [47] attempted to apply theory of diffusion of innovation and new technologies for analyzing the growth of wind power technology in different states of India. Although the policies of the central government of India encouraged growth of the wind power sectors, individual states had varying policy measures result in different rates of diffusion in wind energy in different states. The state level data of cumulative wind power installed capacity is used to obtain the diffusion parameters using a mixed influence diffusion model (Bass model). The diffusion parameters obtained, especially the point of time when an inflection occurs in the diffusion curve (t^*) and the rate of diffusion at the point of inflection (RPI) is used to rank the different states.

Table 2 summarizes the attempts of selected researchers who adopted diffusion model as a tool to analyse diffusion of RETs. The application of existing diffusion model in the context of RET diffusion analysis may have to take two issues into account. First, the total potential of RET is based on available natural resources and thus have natural supply constraints. The potential estimated through the existing diffusion models are calculated for free market situations using the diffusion equation. In the case of RETs, the potential are estimated and given. While these can be used as a reference and assessed for validity through the models, it has to be noted that the potential would not be infinite. Second, the diffusion parameter values estimated through the models could be a basis for effective comparison of diffusion processes if they could be related to explanatory variables. Meade and Islam [15,2] argue that the empirical comparisons have actually received least attention. RET diffusion analysis through the interpretation of parameter values require a correlation between the policies and non policy factors. It is found again in the case of wind power diffusion

Table 2
Use of diffusion models for RETs.

Author and year	Model equation	Type of RET and/country
Collantes (2006) [33]	Technological substitution model. Logistic approach $\left(\frac{n_t}{N-n_t}\right) = \alpha + \beta(t - t_0)$	To study the growth rate of market share of fuel cell vehicles
Masini and Frankl, (2002) [48]	Learning approach	Solar PV systems in southern Europe
Neij (1997) [29]	Use of experience curves $C_{\mathrm{CUM}} = C_0\mathrm{CUM}^{b}$	To analyze the prospects for diffusion and adoption of renewable energy technology
Lund (2002) [27]	Learning by doing (experience curve)	Upfront resource requirements for large-scale exploitation schemes of new renewable technologies.
Lund (2005) [26]	Epidemic diffusion model (Internal influence model)	Market penetration rates of new energy technologies
Isoard and Antonio (2001) [31]	Learning Curve (Cobb Douglas cost function) $C_{j,t} = k_{j,t}^{1/r_j}\prod_{i=1}^{n}P_{i,t}^{\alpha_i/r_j}\ K_{j,t} = r_j\left[A_{j,t}\prod_{i=1}^{n}\alpha_i^{\alpha_i}\right] - 1/r_j$ *Yj,t* being the level of output of technology *j* at time *t*, *Pi,t* the price of input *i* and *r* the returns to scale. The 1-degree homogeneity of the Cob Douglas cost function in input prices is guaranteed by the condition: $r_j = \sum_{i=1}^{n}\alpha_i$	Econometric estimation of learning curve has been performed on solar PV and wind.
Peter et al. (2002) [37]	Rogers Model	Marketing solar PV technology in developing countries
Ibenholt (2002) [28]	A formulation of a learning curve taken from Berndt (1991)	Compares utilization of wind energy in three countries Denmark, Germany and the United Kingdom
Purohit and Kandpal (2005) [46]	Bass model Gompertz model Logistic model Pearl MODEL Equations from the paper	Future dissemination of RET based irrigation water pumping in India
Rao and Kishore (2009) [47]	The Bass model/mixed influence model	Diffusion of wind in different States of India by linking it to a policy index.

analysis in different states as referred above [46], diffusion models can be a basis for such an analysis and in addition, a correlation between the diffusion parameters and the composite policy index can be applied for wind power diffusion assessment.

4. Conclusions

Diffusion modeling is a useful tool for understanding the growth of product or technologies. Although, diffusion of technologies or products does not follow a single uniform pattern and is a complex phenomenon, models have been used to explain the diffusion rates and estimate parameters or coefficients of diffusion model equations. The applications of diffusion models have been mainly limited to commercial products with little or no linkages to government policies. The challenge now is to build up experience in applying diffusion models to analyse diffusion of RETs.

The demand for RETs is being created by the government through a set of policies incentives and regulations. RET applications mainly originated in the market with government subsidy and continue to attract several incentives for varying periods ranging from 5 to 15 years or more. Since RETs face many market barriers, research so far has mainly dealt with the subject of challenges and analysis of barriers that constrain the diffusion of RETs. There is a need for systematic study of RET diffusion using diffusion theory and models. While learning curve approaches have been effective for economic considerations, it is important to correlate the time series data to policy changes and also several factors, particularly, social and technological that influence diffusion processes.

The existing diffusion models can be a useful set of tools to study insights to the diffusion mechanisms and in assessing the effectiveness of the diffusion strategies of renewable energy technologies (RET) in developing countries like India. The application of the selected model for studying RET diffusion could emanate from a theoretical basis that the diffusion processes follow different S curves. However, the diffusion model parameters should be adapted to reflect the issues of RE market potential, policy drivers and technological improvements. There is thus a case for use of diffusion modeling to RETs for policy makers to use diffusion models as a tool to assess the impact of their policies as well as design new renewable energy programmes.

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Appendix A

Table A1
Summary of diffusion model categories and their applications.

Category	Diffusion rate equations represented as dF/dt or $dN(t)/dt$; F – Fraction of adoptions ($F=N(t)/N^u$; N or $N(t)$ cumulative adoption at any given time; N^u – Ultimate potential; a, b, etc. – diffusion coefficients; t – time	Author	Applications
Fundamental diffusion model	External influence: $a(1-F)$	Coleman et al. (1966), Hamblin et al. (1973)	Assumption that mass media – newspapers, radio, and magazines is a major influence; and members of the social systems do not interact and are isolated. New drug by physicians in four mid-western communities; Number of labour strikes and political assassinations in 64 developing nations over a 20 year period.
	Logistic internal influence: $bF(1-F)$	Mansfield (1961), Griliches (1957)	Mansfield investigated several industrial innovations such as pallet loaders, diesel locomotives, and continuous mining machines among firms.
	Gompertz function $\frac{dN(t)}{dt}=bN(t)[\ln N^u-\ln N(t)]$	Gray (1973), Hendry (1972)	Griliches studied diffusion of hybrid corn in 31 States and 132 crops reporting areas among farmers. Dixon applied Gompertz function to Griliches hybrid seed corn data
		Dixon (1980)	Gray investigated diffusion of 12 public policy innovations among the 48 contagious United States
	Mixed influence: $(a+bF)(1-F)$	Bass (1969)	Forecast sales of television sets, dish washers, and clothes dryers.
	Modifications of mixed influence	Webber (1972), Lekvall and Wahlbin (1973), Warren (1980)	Modified to study the impact of location, simulate effect of certain internal and external influences on diffusion patters, forecast market potential of new solar technology and diffusion of educational innovations
Flexible diffusion models	$bF(1-F)^2$	Floyd (1962)	
	$\frac{bF(1-F)^2}{1-F(1-\sigma)}$; $0\le\sigma\le1$	Sharif–Kabir (1976)	
	$(a+bF)(1-F)^{(1+\gamma)}$ $0\le\gamma$	Jeuland (1981)	
	Non-symmetric responding logistic (NSRL) $bF^{\delta}(1-F)$	NRSL (Eastingwood et al, 1981)	Diffusion of two medical innovations – CAT head scanners and CAT body scanners
	Non-uniform influence (NUI) $(a+bF^{\delta})(1-F)$	NUI (Eastingwood et al, 1983)	
	$\frac{b}{1-\theta}F^{\theta}(1-F^{(1-\theta)})$; $0\le\theta$	Von Bertalanffy (1957)	
Extension and refinements	Dynamic diffusion models $\frac{dN(t)}{dt}=(a+bN(t))[f(\underline{S}(t))-N(t)]$ $N(t)=-\frac{a}{b}+\frac{\exp\{a(t-t_0)+b\Phi(t)\}}{[(b/(a+bN_0))]+b\int_{t_0}^{t}\exp\{a(x-t_0)+b\Phi(x)dx\}]}$ Where $N(t=t_0)=N_0$ and $\Phi(t)=\int_{t_0}^{t}f(\underline{S}(x))dx$	Chow (1967), Mahajan and Peterson (1978), Dodson and Muller (1978, Lackman (1978), Sharif and Ramanathan (1981)	Mahajan and Peterson applied their model to membership in UN during the period 1945–1974. Chow examined the natural growth of computers (Gompertz internal influence model) and included "technological change price reduction" effect. Lackman studied growth of a new plastic product in the automotive industry
	Multi innovation diffusion models $\frac{dN_1(t)}{dt}=a_1[N^u-N_1(t)]+b_1N_1(t)[N_1^u-N_1(t)]-c_1N_2(t)[N_1^u-N_1(t)]$ $c1$ represents an interaction between adopters of innovation 2 and nonadopters of innovation 1	Peterson and Mahajan (1978)	Used to hypothesize relationships between innovations. Mahajan and Peterson compared sales growth rate of colour and black and white TV and found the sales growth of black and white complemented that of colour sets.
	Space and time diffusion models $N=f(x,t);\frac{\partial N}{\partial y}=0;\frac{\partial N(x,y)}{\partial t}=(a(x)+b(x)N(x,y))[N^u(x)-N(x,t)]$ $N(x,t)=N^u(x)-\frac{a(x)(N^u(x)-N_0(x))}{1+a(x)+b(x)N_0(x)}\exp(-a(x)+b(x)N^u(x))(t-t_0))/$ $1+\frac{b(x)(N^u(x)-N_0(x))}{(a(x)+b(x)N_0(x))}\exp(-a(x)+b(x)N^u(x))(t-t_0))$	Mahajan and Peterson (1979), Gatignon, Eliashaberg and Robertson (1989)	Mahajan and Peterson reanalyzed data documenting the tractors in 25 states in the central agricultural production region of the US for the period 1920-1964
	Multistage Diffusion Models $\frac{dy}{dt}=\beta x(y+z)+\mu x+\gamma y$ $\frac{dz}{dt}=\gamma y$; $\frac{dN(t)}{dt}=\gamma(N^u(t)-N(t))$	Midgley (1976), Dodson and Muller(1978), Sharif and Ramanathan (1982), Mahajan, Muller and Kerin (1984)	Model divides the potential adopters (customers) and current adopters (triers) into two groups, each based on positive or negative nature of communicated information. Mahajan applied their model to forecast attendance for the movie "Gandhi" in the Dallas, Texas area.

Multi adoption Diffusion Models $N(t+1) = a(t)(N^u - N(t)) + b(N(t) - N(t-1))(N^u - N(t)) + c(t)N(t)$ $N(t+1) = a(N^u - N(t)) + b\left(\frac{N(t)}{N^u}\right)^{\delta}(N^u - N(t)) + cN(t)$	Wind et al. (1981), Lilien et al. (1981), Mahajan et al. (1983)	Forecasting sales for product innovations. Lilien model to forecast sales of ethical drugs.
Diffusion Models with Influencing/change Agents $a(t) = A(\underline{S}(t))$ $b(t) = B(\underline{S}(t))$ $N^u(t) = N^u(\underline{S}(t))$	Robinson and Lakhani (1975), Mahajan and Muller (1979), Dolan and Jeuland (1981), Jorgenson (1983), Kalish (1983), Horsky and Simon (1983), Mahajan and Wind (1985), Mahajan, Muller and Bass (1990), Jain (1992)	Incorporating the influence of pricing, advertising, promotion and technological change into the model.

Mahajan and Petersen (1985).

Table A2
Diffusion model categories.

Category	Model equation	
Models of Cumulative Adoption	1.1.Bass model	$\frac{dF}{dt} = (a + bF(t))(1 - F(t))$
	1.2. Cumulative lognormal	$N(t) = N^u \int_0^t \frac{1}{y\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\ln(y) - \mu)^2}{2\sigma^2}\right) dy$
	1.3. Cumulative normal	$N(t) = N^u \int_{\infty}^t \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(y - \mu)^2}{2\sigma^2}\right) dy$
	1.4. Gompertz	$N(t) = N^u \exp(-b(\exp(-at)))$
	1.5. Log reciprocal	$N(t) = N^u \exp\left(\frac{1}{at}\right)$
	1.6. Logistic	$N(t) = \frac{N^U}{1 + c\exp(-at)}$
	1.7. Modified exponential	$N(t) = N^u - b\exp\ (-at)$
	1.8. Weibull	$N(t) = N^u\left(-\exp\left(\left(\frac{t}{b}\right)^a\right)\right)$
2. Non-linearised trend and non-linear autoregressive models	2.1. Harvey	$\ln N(t) - N(t-1) = a + b_1 t + b_2 \ln(N(t-1))$
	2.2. Floyd	$\left[\frac{1}{1 - N(t)}\right] + \ln\left(\frac{N(t)}{1 - N(t)}\right) = a + bt$
	2.3. Sharif and Kabir	$\ln\left(\frac{N(t)}{1 - N(t)}\right) + \sigma\left(\frac{1}{1 - N(t)}\right) = N^u + at$
	2.4. KKKI	$\left(\frac{bN^u - a^2}{bN^u}\right)\ln(a + bN^u N(t)) - (a+1)\ln(1 = b + (bN^u + a)t$
	SBB (Sharma, Basu, Bhargava (1993)	$N(t) = N(t-1)\exp(a(1(\mathrm{N}(t-1)))$

Meade and Islam (2006).

Table A3
Rationalized forms of various diffusion models.

S. No.	Models	$A(F)$	$G(1-F)$
1.	Coleman	a	$(1-F)$
2.	Mansfield	bF	$(1-F)$
3.	Bass	$a+bF$	$(1-F)$
4.	Floyd	bF	$(1-F)^2$
5.	Sharif–Kabir	$bF/[1-F(1-e)]$	$(1-F)^2$
6.	(a) Easingwood- Mahajan Muller (NSRL)	bF^{d}	$(1-F)$
	(b) Modified NSRL	bF	$(1-F)^{d}$
7.	Non-uniform Influence (NUI)	$(a+bF)^{d}$	$(1-F)$
8.	Jeuland	$(a+bF)$	$(1-F)^{1+r}$
9.	(a) Nedler	Bf	$(1-F)^{e}$
	(b) Von Bertalanffy	$[b/(1-e)]F^{e}$	$(1-F)^{1-e}$
10.	(a)Generalized rational model (GRM-I)	$bF/(1-F+eF)$	$(1-F)$
	(b) Generalized rational model (GRM-II)	$bF/(e+F-eF)$	$(1-F)$
11.	Other possibilities	$a+bF+rF^2$	$(1-F)$
		$[a/(1+F)+bF]$	$(1-F)$
		$[a/(1+F)+bF]$	$(1-F)^2$

Jain et al. (1991).

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